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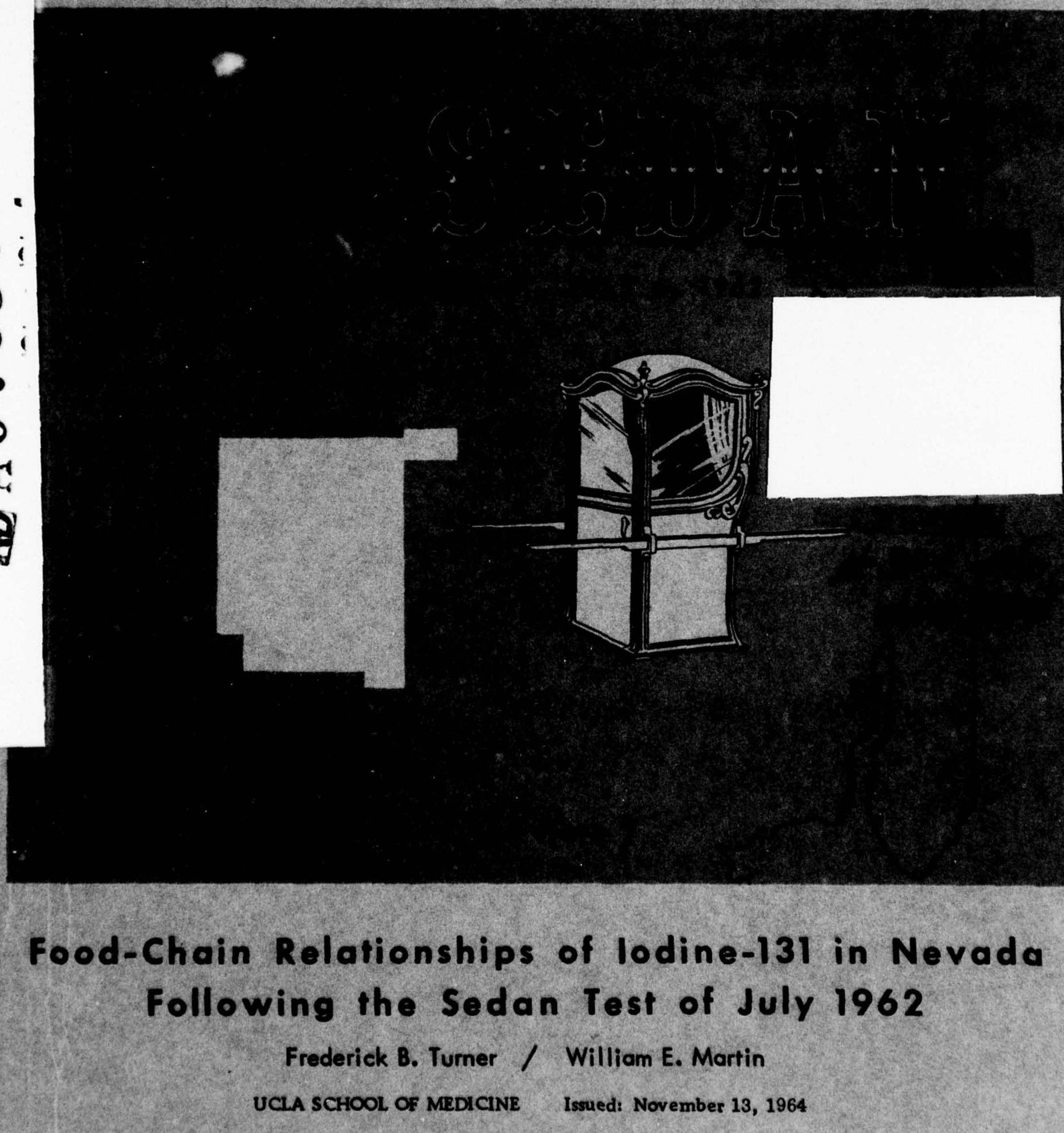

Food-Chain Relationships of Iodine-131 in Nevada Following the Sedan Test of July 1962

Frederick B. Turner / William E. Martin

UCLA SCHOOL OF MEDICINE

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NUCLEAR EXPLOSIONS – PEACEFUL APPLICATIONS

PROJECT SEDAN

PNE-236F

PROJECT 62.83

FOOD-CHAIN RELATIONSHIPS OF IODINE-131 IN NEVADA FOLLOWING THE SEDAN TEST OF JULY 1962

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July 24, 1964

ABSTRACT

Following the Sedan test of July 6,1962, in Nevada, the applicability of mathematical models to food-chain transfers of iodine-131 in natural environments was examined. The amounts of radioiodine measured in the thyroids of jack rabbits collected at 5-day intervals between July 5 and August 5 were compared to levels predicted by models on the basis of estimated levels of radioiodine on vegetation as of July 6. Four areas, from 20 to 110 miles from ground zero, were studied between 5 and 30 days after the test. The basic model was deterministic, but a probabilistic model predicated on the same assumptions was also developed and tested.

The performance of the models was good enough to encourage further work of this nature. We consider it more likely that disparities between observations and predictions are due to errors in estimating input variables than to a flaw in the design of the models. Accurate estimates of daily ingestion of radioiodine, and absorption and uptake by the thyroid are the most difficult to obtain.

Analyses of vegetation samples suggest that the distribution of radioiodine on vegetation after the test was lognormal, not normal. When distributions of radioiodine on vegetation are defined as lognormal, and frequency distributions of thyroid radioiodine in large synthetic populations are generated by the computer, these distributions are also lognormal. Whether such distributions reflect the situ-

ation in nature depends on the validity of the assumptions built into the model. We believe that the model assumptions are qualitatively sound, and that lognormal distributions of radioisotope concentrations in organs are probably characteristic of populations consuming vegetation contaminated by local fallout. This conclusion is supported both by measurements of radioiodine on vegetation at various times between July 11 and August 5, and by analyses of observed distributions of radioiodine in the thyroid of herbivores consuming this vegetation.

The assumption of the Federal Radiation Council that the "majority of individuals do not vary from the average by a factor greater than three," appears reasonable, both on the basis of actual observations and analyses of synthetic distributions of 1000 individuals.

If our measurements of radioiodine on sagebrush (<u>Artemisia</u> <u>tridentata</u>) in the vicinity of Currant, Nevada (110 miles from ground zero), were even close to levels of radioiodine on cattle forage (<u>i.e.</u>, no more than 10 times higher), it is an unavoidable conclusion that had milk been produced in this area during July of 1962, it would have contained radioiodine (2000-3000 $\mu\mu c/1$) temporarily far in excess of the limit of Range II recommended by the Federal Radiation Council (100 $\mu\mu c/1$). Levels would have been higher in areas closer to ground zero. Fortunately, there is little dairying in this part of Nevada.

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FOOD-CHAIN RELATIONSHIPS OF IODINE-131 IN NEVADA FOLLOWING THE SEDAN TEST OF JULY 1962.

1. INTRODUCTION

An important aspect of the assessment and prediction of radiation hazards is the time-specific relationship between fallout radioisotopes on vegetation and the amounts of such material assimilated by herbivores and ultimately consumed by man. One should be able to represent such relationships by mathematical models, so that if the amount of a radioisotope in one compartment of a food-chain is measured, inferences may be drawn as to how much is or will be present in other compartments. Such models should take into consideration the considerable variability which occurs in natural systems--as evidenced by the British work in Australia in 1956[1] and investigations at this laboratory during the test series of 1953[2] and 1955[3]. Herbivores occupying apparently homogeneous environments and presumably exposed to the same radiological hazards, show tissue burdens of radioisotopes which differ greatly. From the standpoint of health physics it is important to understand this variability because the high extremes are more important than modal values. The importance of this point has been recognized by the Federal Radiation Council, which has recommended the arbitrary assumption that the majority of individuals in a population does not vary from the average by a factor greater than three[4].

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Four fallout radioisotopes are considered important in food-chain problems (Sr-90, Sr-89, Cs-137, and I-131), but recently there has been particular interest in environmental problems involving radioiodine* (*e.g.*, see Pendleton[5], Reiss[6], Knapp[7], Martin[8], Turner[9], and the summary-analysis of the 1962 Congressional Hearings[10]).

In considering the quantitative relationships between fallout radioiodine and I-131 in human foods, it is possible to seek some simple empirical relationship--*e.g.*, the ratio of radioiodine per liter of milk to the gross gamma activity on the ground. This approach has been adopted by Knapp, who indicates that for a number of past events involving the release of radioiodine to the environment, the ratio of the maximum amount of I-131 (I_{max}) in milk (μμc/liter) to the gross gamma activity (mr/hr) on the ground at H + 24 (r_o) varied from about 18,000 to 220,000[7]. Such an approach certainly avoids any difficulties in attempting to evaluate intermediate steps in this relationship, and may have merit in emergency situations where no other estimates of potential hazards are available.

From a theoretical standpoint it is more fruitful to consider the contamination of milk by I-131 as the last link in a chain of related events, and to attempt to develop a step-by-step representation of this process by means of a compartment model. Such a model could be arranged in 3 compartments: iodine on cattle forage, iodine in

* Radioiodine hereafter refers to I-131

cattle, and iodine in milk (or a fourth compartment, the ground surface, could be added if desired). But would such a model perform adequately when applied to a real environmental situation? The general idea might be evaluated using a more simple model, e.g., one involving only 2 compartments.

Prior to the Sedan test of July, 1962, we decided to test the model approach using the time-specific relationship of radioiodine on desert vegetation to radioiodine in the thyroids of jack rabbits consuming this vegetation. The model used has been discussed previously by French[11] and French and Van Middlesworth[12]. The model is also given in our preliminary report, PNE-236P[13], and is repeated here in slightly modified form for convenience:

$$A = \frac{I \times D \times F}{\lambda_E - \lambda_p} \left(e^{-\lambda_p t} - e^{-\lambda_E t}\right)$$

A = amount of I-131 in thyroid of consumer

I = amount of I-131 per gram of vegetation on day of contamination

D = number of grams of vegetation consumed per day

F = fraction of ingested I-131 reaching thyroid of consumer

λ_p = physical decay constant of I-131

λ_E = effective decay constant of I-131 in thyroid of consumer

t = time (in days) after the contaminating event

e = 2.7183

When t is defined as the number of days following the introduction of I-131 into the environment, the model predicts the amount of

radioiodine in the thyroid of a consumer (at time _t_) in terms of a specified initial level of contamination of food, I. (See PNE-236P, Appendix D, for an illustration of the calculations).

Certain assumptions regarding the thyroidal uptake of dietary I-131 by jack rabbits (F), the amount of food consumed daily by jack rabbits (D), and the effective half-life of I-131 in the thyroids of jack rabbits (from which λ_E is derived) are given in PNE-236P and are recapitulated later (see pp. 30-32). The half-life of radioiodine on vegetation is assumed to be 8 days in the model above. We reasoned that it would actually be less than 8 days and estimated the effective half-life (λ_v) directly by sequential measurements of radioiodine on vegetation[8].

A preliminary discussion of this study may be found in PNE-236P and in papers by Martin[8] and Turner[9]. However, other issues arise and it is the purpose of this report to discuss these problems. Specifically, the questions are:

1. Does the application of a 2-compartment model to an environmental situation involving radioiodine contamination appear feasible, _i.e._, can one predict the amounts of radioiodine in herbivores as a function of time and the amount of radioiodine in their diet? Can this approach be expanded to the broader problem of vegetation-cow-milk relationships?

2. Can inferences be drawn as to the type of frequency distribution which the thyroid burden of herbivores may be expected to exhibit? Is this distribution predictable on the basis of vegetation analyses? Is the Federal Radiation Council assumption that the majority of individuals in a population be considered to lie within 3 times the mean reasonable?

3. In view of Knapp's discussion of radioiodine in Nevada milk following the Small Boy test of July, 1962 (and based primarily on measurements of radioiodine in milk from Caliente and Alamo, Nevada)[7], do our data shed any light on possible public health hazards in southern and central Nevada following the Sedan test?

2. PROCEDURE

2.1 Collection and Radiochemical Analysis of Samples

Methods are fully described in PNE-236P. Basically, the procedure involved: 1) the collection of background materials (bulk plant samples and jack rabbits) from areas north of the Nevada Test Site in June of 1962, 2) the collection of similar samples, primarily from four areas, at 5-day intervals between July 11 and August 5, 1962, and 3) the determination of amounts of I-131 in the bulk plant samples and the thyroids and stomach contents of the rabbits.

Initial levels of radioiodine (as of July 6) on natural vegetation in four areas were estimated by decay corrections based on a 5.5 day effective half-life (see PNE-236P, p. 34). Levels of

thyroid radioiodine predicted on the basis of these estimates were compared with the amounts of thyroid radioiodine actually observed in jack rabbits from the four areas.

In this report the procedure is extended to include predictions of thyroid radioiodine based on analyses of the I-131 in the stomach contents of rabbits.

2.2 A Probabilistic Version of the Model

2.2.1 Design of the Model

The model given on page 13 is deterministic. When the 5 input variables are prescribed the model yields a single value for each value of t employed. Results of this procedure, involving calculations for D + 5, D + 10....D + 30, are discussed in PNE-236P (see also Figure 2).

If one wishes to consider the possible variation of a "prediction" for any time t, one must know the variability of each input parameter and the type of frequency distribution generated by the interaction of these parameters. Although the variation of the inputs was known approximately, it was not possible to predict the interaction of the variables theoretically. Instead, the deterministic model was revised as a probabilistic simulation of the experience of an herbivore in an area contaminated by radioiodine, and the simulation was programmed for IBM 7090 computer solution.

The revision is simply a discrete version of the deterministic model, with an interval of one day between meals. When the interval is zero, as if feeding were continuous, the discrete version is identical with the continuous. The advantage of the discrete version is that it facilitates the simulation of the feeding experience of a group of individuals over a period of time. The purpose in designing the stochastic version of the model is to permit the variables to take on different values and to examine the influence of chance variation in the inputs on the predictions of the model.

It is easier to visualize the stochastic model if one considers what occurs when an herbivore occupying a fallout field consumes a series of meals, each containing a varying amount of radioiodine. Ultimately one wishes to estimate the amount of radioiodine (A) in the thyroid of the consumer at the end of some arbitrarily defined period of time. For example, the amount of thyroid radioiodine after 30 days is the sum of 30 terms. Each term represents the radioiodine remaining in the thyroid from one of 30 meals. From a given meal containing iodine-131, some fraction (F) of the radioiodine is absorbed and reaches the thyroid. The 30-day thyroidal uptake of radioiodine may be given as follows:

$$F(D_1C_1 + D_2C_2.... + D_{30}C_{30}) \qquad (1)$$

where D_i is the number of grams of food consumed, and C_i is the amount of radioiodine per gram of food. This series does not

represent the amount of radioiodine in the thyroid after 30 days. The radioiodine which reaches the thyroid is lost both by secretion and radioactive decay, so that it declines exponentially with an effective half-life reflecting these two processes. Hence, the amount of radioiodine which reaches the thyroid on day one is reduced by the end of 30 days to:

$$FD_1 C_1 E^{30} \quad \text{where } E = (1/2)^{1/b} \tag{2}$$

and b is the effective half-life of radioiodine in the thyroid (in days).* The amount of radioiodine ingested on the ith day after fallout and remaining 30 days after fallout is:

$$FD_i C_i E^{30 + 1 - i} \tag{3}$$

The required series for 30 days is thus:

$$A = FD_1 C_1 E^{30} + FD_2 C_2 E^{29} \ldots + FD_{30} C_{30} E \tag{4}$$

So far C_i has been taken as the amount of iodine-131 per gram of food at the time of consumption. Yet we wish to derive C_i from the amount of radioiodine on vegetation on the first day. The loss of radioiodine from vegetation is approximately exponential, but the effective half-life v_i, varies from day to day. The relationship between the amount of radioiodine on vegetation consumed on day two and the original amount of iodine-131 on vegetation may be expressed as:

$$C_2 = x_2 V_1 \tag{5}$$

---

*$b = .693/\lambda_E$ and $e^{-\lambda_E t} = E^t$

where: x_2 = the original amount of radioiodine on the vegetation making up the meal consumed on the second day

and $V_1 = (1/2)^{1/v_1}$ (6)

On the *i*th day, the relationship would be:

$$C_i = x_i V_1 V_2 V_3 \ldots V_{i-1} \quad (7)$$

or

$$C_i = x_i \prod_{j=1}^{i-1} V_j \quad (8)$$

The expression for A given in (4) can now be rewritten:

$$A = F(D_1 x_1 E^{30} + D_2 x_2 V_1 E^{29} + D_3 x_3 V_1 V_2 E^{28} \ldots + D_{30} x_{30} \prod_{j=1}^{29} V_j E) \quad (9)$$

2.2.2 The Frequency Distributions of the Input Parameters

It is now necessary to assign frequency distributions to the variables discussed in Section 2.2.1. F and *b* are considered constant for any one individual, but not the same in all individuals. F was chosen randomly from 114 values ranging from 0.05 to 0.35 (see Appendix A). The nature of the distribution was inferred from the work of French[11]. The value of *b* (days) was chosen randomly from the following distribution:

1.5, 2.0, 2.0, 2.5, 2.5, 2.5, 3.0, 3.0, 3.5

The values of D_i and $\underline{v}_i$ change from day to day. D_i was chosen at random from the following distribution of values:

80, 90, 90, 100, 100, 100, 100, 110, 110, 120

and the values of $\underline{v}_i$ (days) were similarly selected from the following:

5.0, 5.33, 5.33, 5.5, 5.5, 5.5, 5.75, 5.87, 6.0

In the preceding discussion the successive amounts of radioiodine per gram of vegetation consumed have been expressed as functions of $\underline{x}_1 \ldots \underline{x}_{30}$. So we must now consider the nature of the distribution of radioiodine per gram on the first day. Let this distribution be represented by values of $\underline{x}$. A typical distribution of $\underline{x}$ (based on 41 values from Penoyer Valley and developed as described in Section 2.1), and the distribution of X (= log $\underline{x}$) are portrayed in Figure 1. Because of its shape, the distribution of X was assumed to be normal, with mean and variance equal to the mean and variance of the sample values of X. The means and variance of four such distributions of X are given in Table 1.

Because $\underline{x} = 10^X$, 30 values of $X_1 \ldots X_{30}$ were selected at random from normal distributions (as defined in Table 1), and the antilogarithms of these numbers defined the values of $\underline{x}_i$ (with $\underline{i}$ = 1 to 30).

2.2.3 Operation of the Model

The simulation was programmed in the following form:

$$A = F \sum_{i=1}^{n} E^{n+1-i} D_i 10^{X_i} \prod_{j=1}^{i-1} Vj.$$

where: $E = (1/2)^{1/b}$ and $V_j = (1/2)^{1/v_j}$

After 4 days, this expression (in expanded form) would be as follows:

$$A = F\left[\underset{i=1,\ j=o}{E^4 D_1 10^{X_1}} + \underset{1=2,\ j=1}{E^3 D_2 10^{X_2} V_1} + \underset{i=3,\ j=2}{E^2 D_3 10^{X_3}(V_1 V_2)} + \underset{i=4,\ j=3}{E D_4 10^{X_4}(V_1 V_2 V_3)}\right]$$

Table 1 - Estimated radioiodine on vegetation ($\mu\mu c/g$) as of July 6, 1962, based on decay corrections of bulk samples of vegetation and of stomach contents of jack rabbits ($\lambda_v = 0.126$). The antilogarithm of the mean of the logs is the geometric mean of the distribution and is not the same as the arithmetic mean.

	Mean of logs	Variance	Arithmetic mean of distribution (and sample size)
Groom Valley			
vegetation	4.075	0.228	17481 (30)
stomach contents	3.611	0.272	6533 (27)
Penoyer Valley			
vegetation	3.428	0.120	3695 (41)
stomach contents	3.488	0.100	3930 (36)
Railroad Valley			
vegetation	3.184	0.017	1656 (29)
stomach contents	3.218	0.058	1980 (25)
Currant			
vegetation	2.825	0.110	890 (31)
stomach contents	2.494	0.100	414 (25)

Thus, the daily decline in radioiodine on vegetation is simulated and day to day variations in the rate of loss are permitted to occur by chance. Most important, the initial amount of radioiodine per gram of food is permitted to vary, because an herbivore feeding at

random in a fallout field will consume heavily contaminated foliage on some days and lightly contaminated food on others. The 30-day experience of a single hypothetical consumer was simulated in the manner described above. Only the cumulative totals of thyroid radioiodine at 5, 10, 15, 20, 25, and 30 days were printed out. By repeating this procedure, distributions representing synthetic "populations" of consumers could be built up by the computer.

In the first simulation, based on radioiodine levels taken from bulk plant samples, the program generated 24 frequency distributions of 100 individuals each, representing theoretical thyroid radioiodine levels in the four study areas as of 5, 10, 15, 20, 25, and 30 days after the original deposition of radioiodine on July 6. The second simulation, involving the same areas and dates, produced 24 frequency distributions of 1000 values each. The third simulation involved radioiodine levels predicated on stomach samples, but was in other respects like the first.

3. RESULTS

3.1 Recapitulation of Earlier Results

The entire array of radioiodine determinations is given in PNE-236P (Appendix B). In the earlier report, and also here, attention is primarily focused on stations in four areas (at distances of 20 to 110 miles from ground zero) between 5 and 30 days after the Sedan test. We selected those stations from which we had the most data and on the basis of their location within the fallout pattern (as defined

by E.G. & G.[14]). The general conclusions expressed in PNE-236P are reviewed for convenience: 1. Radioiodine disappeared from vegetation with an effective half-life of about 5.5 days (usually from 4.5 to 6 days). This was generally true in all 4 areas and apparently independent of time after fallout deposition.

2. There were differences between levels of radioiodine measured on bulk vegetation samples of sagebrush (*Artemisia tridentata*) and shadscale (*Atriplex confertifolia*) and those measured from stomach contents of rabbits from the same areas. The differences were not consistently in the same direction. 3. Using F = 0.16 and initial levels of radioiodine on vegetation estimated from measurements of bulk plant samples, the model predicted amounts of thyroid radioiodine which we believe differed significantly from those observed. There was no consistent pattern to the disparities between predicted and observed values, *i.e.*, the model overpredicted in two areas and underpredicted in the other two. However, the decline of measured and predicted thyroid I-131 with time was about the same, suggesting that the values adopted for λ_V and λ_E were reasonable. It appeared more likely that estimates of F and I may have been incorrect.

4. Differences in vegetation sampled in the field and that actually consumed by rabbits may have accounted, in part, for discrepancies between observations and predictions based on plant samples.

3.2 Close-in Observations

Data from near ground zero were not discussed earlier. The Sedan ground zero was located in Area 10, in the northernmost part of Yucca Flat. Here, particularly within 2 to 5 miles east of ground zero, we found much higher levels of radioiodine, both on vegetation and in rabbit thyroids, than at any of the more distant stations. Because the conditions in Area 10 were well within the limits of the Test Site, the data have no public health implications. However, these iodine levels are of interest as an illustration of what might be expected close-in following the underground detonation of a device like that used in the Sedan test (Table 2).

Even 10 days after the test, levels of I-131 on vegetation and in rabbit thyroids in Area 10 were higher than any observed in Groom Valley five days after the test. Evidently, the thyroids of some rabbits in Area 10 accumulated several microcuries of I-131 during the first 3 or 4 days following the test. (Observe that thyroid I-131 burdens in excess of a microcurie were measured on July 16 and even as late as July 28).

3.3 Radioiodine in Stomach Contents of Jack Rabbits

As implied in Section 3.1, our initial analyses were based on the assumption that bulk plant samples were adequate representations of rabbit diets, and that an evaluation of the radioiodine in such samples would be a satisfactory index of dietary intake. Stomach samples from rabbits taken in Groom Valley and near Currant had less

Table 2 - Mean radioiodine levels close-in following the Sedan test of July 6, 1962.

	July 16	July 23	July 23	August 2	August 6
I-131 on native vegetation (mμc/g)					
2 stations east of crater	95		12		10
3 stations north of crater		5.9	1.4	4.5	1.0
I-131 in stomach contents of jack rabbits (mμc/g)					
2 stations east of crater	15		9		3.5
3 stations north of crater		3.2	1.4	0.7	0.7
I-131 in thyroids of jack rabbits (mμc/gland)					
2 stations east of crater	1287		819		58
3 stations north of crater		241	212	57	108

radioiodine than bulk samples of sagebrush from the same areas, while stomach contents of rabbits from Penoyer Valley and Railroad Valley had more radioiodine than corresponding bulk samples of shadscale. We believe it is significant that in the first two areas the model predicted more thyroid radioiodine than was actually observed, while in the latter two areas the model underpredicted. It would seem desirable then, that the effect of using the radioiodine determinations based on stomach contents as indices of initial levels of radioiodine

contamination of rabbit food should be explored.*

The estimates of initial levels of plant contamination in four areas (based on stomach samples) are given in Table 1. These values may be used in the deterministic model to predict amounts of thyroid radioiodine between 5 and 30 days after the test, as was done earlier with values based on radiodine analyses of bulk vegetation samples[13]. The results are shown in Figure 2. Predictions based on bulk vegetation samples are repeated for convenience.**

When predictions are based on radioiodine analyses of stomach contents the accord between predicted and observed values is somewhat improved and the disparities are now generally consistent.

3.4 Results of First and Second Computer Simulations

These experiments were both based on initial radioiodine levels estimated from bulk plant samples. In the first instance, 24 distributions of 100 individuals, and in the second case 24 distributions of 1000 individuals, were generated.

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* If neither sagebrush nor shadscale is representative of rabbit diets the question arises as to what plant species were being consumed. Currie suggests that the main summer forage was made up of grasses[15].

** Actual values on which Figure 2 is based are given in Appendix B.

3.4.1 Distributions of 100 individuals

Figure 3 shows 6 distributions selected from 24 produced by the computer. Also shown are actual observations made under conditions simulated by the computer program. When one has only a few measurements, it is often difficult to assess whether these measurements are in accord with the model's predictions or not. However, when the observations tend to exceed predictions, it is usually possible to infer whether the observations are drawn from some distribution other than that generated by the computer.* For example, in Figures 3 A and 3 B, appreciable proportions of the measurements made fall entirely beyond the upper limits of the synthetic distributions (or beyond the 99% level). In 3 B three of the 5 measurements fall close to the mean of the synthetic distributions, but two are beyond its upper limit. According to the predictions, the probability of a value exceeding 100 mμc is very small, perhaps less than .01. Hence, the occurrence of two values of more than 100 mμc in a sample of 5 implies that we are dealing with two different distributions. The implications of Figure 3 A are even more definite.

When the observations tend to be less than predictions, the picture is not always so clear (see 3 C and 3 D). In one of the

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* In the following discussion it is assumed that the distributions of 100 values depict accurately the form of the true "theoretical" distribution.

examples (3 C), some of the observations actually fall below the lower limit of the synthetic distribution. But in Figure 3 D the observations, although clustered on the low side of the synthetic distribution, are not so statistically unlikely as the very high observations illustrated in Figures 3 A and 3 B.

The mean of the synthetic distribution shown in Figure 3 D is 48.5 and 46% of the cases fall above 40 mμc. If the 5 observations were drawn from a population approximating the synthetic distribution, one would expect all 5 of the observations to fall below 40 less than 5% of the time ($0.54^5 = .046$). Figures 3 E and 3 F illustrate instances where the predictions and observations seem to be in accord.

3.4.2 Distributions of 1000 individuals

The results given above neither prove nor disprove the applicability of the model. Significant disparities between observations and predictions do exist, but whether these represent some intrinsic flaw in the design of the model, or errors in estimating input parameters, cannot be established. However, if one assumes that the model represents a good approximation of events in nature, and that the variability of the inputs is reasonably expressed in Section 2.2.2, then one may inquire as to the general form of the frequency distribution of thyroid radioiodine in a large population. The irregularities in the distributions of 100 individuals may be largely eliminated by increasing the size of the synthetic distributions to 1000. The form of several such distributions is illustrated in Figure 4, and the

statistical attributes of 24 are given in Table 3.

3.5 Results of Third Computer Simulation

Here the initial levels of radioiodine on vegetation were estimated from analyses of stomach samples. Figure 5 shows four synthetic distributions generated in this manner and the actually observed amounts of thyroid radioiodine.

4. DISCUSSION

4.1 Evaluation of the Model

In view of the nature of the problem, the differences between observations and predictions are not enormous. However, we feel that something other than chance is involved in these differences. Are the disparities due to a flaw in the model or to errors in estimating one or more of the input variables? Some light may be shed on this problem by considering the various parameters used in the model, and the manner in which they were defined.

1) Amount of food ingested daily (D). The value of 100 grams per day used in the deterministic model, and the distribution of D_i used in the stochastic version, were based on a communication from Currie[15] and a paper by Arnold[16]. Both worked with jack rabbits, but Currie's work was in Utah and Arnold's in Arizona.

2) The initial amount of radioiodine per gram of vegetation (I). This parameter is difficult to estimate because it is exceedingly variable, and because the contamination must be expressed in terms of the forage actually consumed by the herbivore. We have concluded that

Table 3-Some statistical attributes of synthetic populations of 1000 individuals generated by a probabilistic model of radioiodine food-chain transfer. Numbers represent mμc of radioiodine in thyroids of herbivores.

Area	D+	Mean	Standard Deviation	Standard Error of Mean	Maximum	Minimum	Range	Per Cent of Population Exceeding 3 Times the Mean
Groom Valley	5	585.4	487.3	15.4	4611.4	52.1	4559.3	1.2
	10	479.1	364.4	11.5	3785.7	31.6	3754.1	2.6
	15	295.7	205.8	6.5	1359.2	23.5	1335.7	1.9
	20	174.1	124.5	3.9	1238.6	5.3	1233.3	1.4
	25	99.6	71.5	2.3	511.3	5.6	505.7	2.1
	30	54.2	39.4	1.2	330.0	3.5	326.5	2.0
Penoyer Valley	5	99.7	62.6	2.0	413.3	13.5	399.8	1.5
	10	79.6	46.5	1.5	319.7	7.8	311.9	0.7
	15	50.1	31.1	1.0	240.8	2.8	238.0	1.3
	20	29.0	18.4	0.6	111.8	2.2	109.6	1.5
	25	16.1	10.4	0.3	74.1	1.4	72.7	1.4
	30	8.8	5.9	0.2	58.7	0.9	57.8	1.0
Railroad Valley	5	43.9	19.1	0.6	136.4	7.2	129.2	0.1
	10	35.0	16.9	0.5	121.0	5.7	115.3	0.2
	15	21.9	11.3	0.4	79.9	3.0	76.9	0.4
	20	12.7	7.0	0.2	51.1	2.0	49.1	0.7
	25	7.1	4.1	0.1	28.4	0.9	27.5	1.2
	30	3.9	2.3	0.08	15.9	0.5	15.4	1.3
Currant	5	25.0	16.1	0.5	117.0	1.5	115.5	1.5
	10	19.3	11.7	0.4	77.5	2.3	75.2	1.3
	15	12.1	7.4	0.2	47.7	1.1	46.6	1.0
	20	7.0	4.3	0.1	29.0	1.0	28.0	1.2
	25	3.9	2.5	0.08	16.8	0.3	16.5	1.3
	30	2.1	1.4	0.04	10.0	0.2	9.8	1.3

some of the disagreement between observations and predictions based on bulk vegetation samples stemmed from analyzing plant species not consumed by rabbits. The picture is improved somewhat by using radioiodine analyses of stomach contents to estimate the initial levels of radioiodine on vegetation. If one knew what plant species were consumed by an herbivore, and what parts of the individual plants were eaten, bulk samples would probably be satisfactory. Another problem arises when samples collected, say, 20 days after the test are used to estimate levels of radioiodine on the day of the test. We corrected for the disappearance of radioiodine from vegetation by using a 5.5 day half-life. There is considerable variability in this parameter and the use of a 5.0 day half-life could probably be justified as well as one of 5.5 days. Whether 5.0 or 5.5 is used to calculate λ_v in the model does not make a great deal of difference, but when plant samples collected in the latter part of July or early August are corrected to July 6, the use of a half-life of 5.0 days instead of 5.5 days may increase estimates of initial levels of radioiodine by as much as 20%.

Finally there remains the problem of volatilization. Martin has discussed the possible loss of radioiodine from vegetation samples by volatilization[8]. That is, some of the radioiodine present at time of collection escapes before the material can be chemically assayed. The stomach contents were air-dried in a hood at room temperature. So here again there was an opportunity for escape by volatilization. We

conclude that if radioiodine analyses of vegetation are anticipated, material should be placed in NaOH or thiosulfate solution to stabilize the radioiodine present.

3) The absorption of ingested radioiodine and uptake by the thyroid (F). We used French's estimate of F=0.16 for summer jack rabbits[11]. Adult jack rabbits cannot be kept in captivity conveniently so we did not attempt to estimate F experimentally. We did perform a feeding experiment with Dutch rabbits in order to determine whether the biological availability of radioiodine from Sedan fallout was extraordinary. The results of this experiment are given in PNE-236P, and indicate that the uptake of radioiodine from Sedan fallout by Dutch rabbits is about the same as that observed in earlier experiments. Still, we have no way of knowing how suitable French's estimate of F for Idaho jack rabbits is for Nevada jack rabbits. F is variable, and values as high as 0.35 were observed by French. This variability was expressed in the stochastic version of the model but not, of course, in the deterministic (Appendix A).

There is also the possibility that some radioiodine was inhaled by jack rabbits during the early days following the Sedan test[9]. This mechanism is not incorporated in the model.

4) The rate of loss of radioiodine from vegetation (λ_v). This parameter was estimated directly by repeated measurements in the field [8], and is fairly close to an earlier estimate of Chamberlain and Chadwick [17]. The validity of our estimates could have been influenced by losses due to volatilization between the time the samples were collected in the field and the time of radiochemical analyses.

5) The rate of loss of radioiodine from the jack rabbit thyroid (λ_E). The mean effective half-life, 2.5 days, and the distribution of this parameter were both based on work by French in Idaho[11] ($.693/2.5 = \lambda_E$).

When the first three variables are defined, modest changes in the values of λ_v and λ_E do not modify the predictions of the model markedly. If one ignores the differences between the magnitudes of the predicted and observed values, and considers only the rate of decline of these values, one may show that the two half-life parameters (which determine this rate) are approximating fairly closely the observed rate of loss of radioiodine from jack rabbit thyroids. Consider each observation and prediction for D+5 as unity. The the subsequent values (on D + 10, D + 15, etc.) may be expressed as some fraction of unity. The results of this procedure are shown in Table 4 and Figure 6.

There is a general tendency for observed levels to decline more rapidly than the model predicts. However, this discrepancy is not great and we conclude that errors in estimating λ_v and λ_E are not involved to a great degree in the disparities between observations and predictions of thyroid radioiodine.

Table 4-Observed and predicted rates of decline of thyroid radioiodine in jack rabbits following the Sedan test of July, 1962. Values as of July 11 (D+5) are taken as unity.

Days after test	Predictions	Observations				
		Groom Valley	Penoyer Valley	Railroad Valley	Currant	Mean of observations
10	.78	.83	.79	.77	.27	.67
15	.48	.34	.38	.55	.18	.36
20	.27	.18	.15	.20	.22	.19
25	.15	.13	.12	.26	.06	.14
30	.08	.03	.10	.11	.04	.07

In view of the possible errors in estimating D, I and F, there can be no reason to reject the model as formulated. For example, any combination of errors causing a two-fold reduction in the product of these parameters could account for the disparity between observations and predictions.

While it may never be possible to prove rigorously that the model simulates exactly what is happening in the environment, we conclude that the model merits further investigation. Future efforts toward improving the estimates of input variables might well result in very close accord between observations and predictions.

There remains the problem of the variability actually encountered in fallout fields and theoretically predicted by the stochastic simul-

ations. Is there anything to be gained by a probabilistic approach? Could one not simply infer the nature of the distribution of thyroid radioiodine in a population of consumers by calculating the mean and variance of a sample? This can be done, but our data suggest that such a procedure should be prefaced by a log transformation of the data. This conclusion is based on two points. First, consider the distribution of radioiodine on plants. It appears more likely that this distribution is lognormal than normal (see Fig. 1, which is typical of samples from all four areas). It will be recalled that the distribution of radioiodine on vegetation was assumed to be lognormal for the purposes of the computer program, and this probably accounts for the skewed nature of all of the synthetic distributions--which are normal when plotted semilogarithmically. Second, consider the nature of the actual distributions of observations. We have only small samples with which to work, but it is possible to infer something of the nature of the distribution from which the observations were drawn. Two samples from Penoyer Valley are considered in Table 5, one collected on July 16, the other on July 26.

The actual observations and the means and variances of the samples are given. It is possible to construct normal curves fitted to the arithmetic mean and variances of the samples, and lognormal curves fitted to the geometric means and variances. Both types are illustrated in Figure 7. The distributions fitted to the geometric means appear to give a better fit. Our conclusions are also supported by the findings of Snyder and

Table 5 - Analyses of two samples taken in Penoyer Valley during July of 1962.

	July 16	July 26
Observations (μμc of I-131 per thyroid)	388, 209, 205, 195 172, 170, 130, 115 106	117, 37.1, 29.2 28.6, 26.1, 20.9, 20.7 12.6
N	9	8
Arithmetic mean	187.7	32.4
Variance	7097	1103
Geometric Mean	174.5	29.1
Variance of logarithms of observations	.0287	.0789

Cook, who analyzed the frequency distributions of amounts of trace elements and various radionuclides in human populations.[18,19] They stated: "The data now available are not sufficient to determine the form of the distribution of values, but suggest that it is not a normal distribution, generally being skewed to the high side."

From our investigations, the arbitrary assumption that the majority of individuals in a population do not differ from the mean by a factor of more than 3 appears safe. In only two of 133 jack rabbits (in 24 samples ranging from 5 to 9 individuals), did the thyroid radioiodine burden of an individual exceed 3 times the sample mean. Furthermore, Table 3 shows that only 1 or 2 percent of the synthetic populations

of 1000 individuals exceeded this factor.

The stochastic simulations also permit some insight as to the cause of the variability of thyroid radioiodine in consumer populations. From a theoretical point of view the probabilistic approach holds the promise of not only linking the various events in the food-chain transfer of radioiodine from vegetation to consumer, but also of estimating the likely variability in one compartment of the environment when one has only data pertaining to another.

4.2 Sedan Radioiodine Levels in Nevada and Radioiodine in Milk

At no time in the course of our investigations did we make determinations of radioiodine in milk from the areas studied. Groom Valley lies within the boundaries of the Test Site, and in the three off-site localities (Penoyer Valley, Railroad Valley and Currant) there is little dairy practice because the range forage is poor.* The few dairy cattle maintained in these areas "normally graze on improved irrigated pasture rather than on desert range...".[20] Thus, some milk is produced in the regions considered, and the U. S. Public Health Service has reported radioiodine in milk collected near Fellini's Ranch (3200 $\mu\mu c/l$ on July 23), in the White River Valley (730 $\mu\mu c/l$ on July 25), and in Ely (2800 $\mu\mu c/l$ on July 24).[21] All of these localities are within the Sedan fallout pattern. It is pertinent, then, to inquire as to the possible

---

*"Dairy cattle as a rule do not graze desert range in central and southern Nevada...Milk production would be so low under these conditions... that it would not be practiced by anyone in this area."[20]

effects of the Sedan test, particularly when one recognizes that the U. S. Public Health Service data were taken more than two weeks after the event.

The first problem is to estimate the degree to which cattle food was contaminated. There is no convenient way to compare the retention of fallout by _Atriplex_ or _Artemisia_ with that of plants regularly consumed by dairy cattle. Cattle forage on improved pastures, (_e. g._, alfalfa), is much more dense than sagebrush in southern Nevada, so the total amount of radioiodine per acre _on foliage_ will be much higher in an alfalfa field than in sagebrush desert. However, it is the amount of radioiodine per unit weight of plant material that is important to the herbivore. In sagebrush desert, cattle range over larger areas in order to obtain their daily ration. _Artemisia_ is an efficient retainer of fallout particles. In the one study where its retention was compared directly with that of alfalfa, leaves of sagebrush retained almost twice as many particles/cm^2 as did alfalfa, although the gross β activity /cm^2 of sagebrush foliage was half that of alfalfa. On both species over 80% of the retained particles were less than 44μ in diameter.[22]

The levels of radioiodine on vegetation as of July 6 have been estimated both from bulk vegetation samples (of _Atriplex_ and _Artemisia_) and from material in the stomachs of rabbits. Perhaps none of these values is pertinent with regard to food consumed by cattle. However, this problem should be considered--even if in an abstract way. We have adopted the levels of radioiodine on _Artemisia_ in Groom Valley

(about 20 miles from ground zero) and in the vicinity of Currant (about 110 miles from ground zero) as representative of levels which might occur on cattle forage. These values are 17.5 mμc/g and 0.9 mμc/g respectively (see Table 1).

If a cow consumes 20 pounds (9 kg) of dry material per day, the first day's diet is 158 μc in Groom Valley and 8μc at Currant. In the hypothetical case described by Garner it was assumed that 1/4 $\mu c/m^2$ of vegetation (= 4.4 mμc/g) was deposited and that the cow's first day's diet was 40 μc.[23] Garner also assumed that radioiodine disappears from vegetation with a half-life of 8 days, and under these conditions the amount of radioiodine in milk reaches a maximum of 0.16 μc/l 2 days after initial contamination, and declines fairly regularly to 0.10 μc/l 10 days after contamination. If the milk were consumed immediately, a person drinking one liter a day during the first 10 days after deposition of radioiodine would consume 1.34 μc of I-131. The Garner model makes no assumption as to when the milk is consumed, merely defines the amount of radioiodine per liter at time of milking.

Using Garner's assumption, the milk levels expected in Groom Valley would be about 0.53 μc/l (with a maximum of about 0.63 μc/l;and 0.027 μc/l, with a maximum of 0.032 μc/l, in the Currant area (Table 6).

Table 6-Estimates of deposition of radioiodine on sagebrush, and potential levels of radioiodine in milk, following the Sedan test of July, 1962. The Federal Radiation Council recommends no more than 0.1 mμc per day (or 36.5 mμc per year) for infants; 1.0 mμc per day (or 365 mμc per year) for adults.[24]

	Garner's hypothetical case	Groom Valley (20 miles)	Currant (110 miles)
Estimated initial deposition of I-131 (mμc/g)	4.4	17.5	0.9
I-131 consumed by cow on first day (μc)	40	158	8
Predicted amounts of I-131 in milk (mμc/l			
Maximum*	160	632	32
Mean	134	529	26
Maximum**	-	580	30
Mean	-	431	22

* assuming effective half-life of 1-131 on vegetation is 8.0 days

**assuming effective half-life of 5.5 days

However, radioiodine disappears from vegetation more rapidly than assumed by Garner so this fact should be considered. If one assumes a half-life of 5.5 days, then the maximum levels would be about 0.58 μc/l in Groom

Valley and about 0.03 μc/l at Currant (Table 6). Assuming a lag of 4 days in processing and distribution of milk would reduce the radioiodine to about 70% of these levels.

We cannot define what relationship the deposition of radioiodine on sagebrush has to the contamination of cattle food. We believe it unlikely that the amount of I-131 on sagebrush differs from that on cattle food by more than a factor of 5. Even a 10-fold reduction in the prediction in Table 6 would still imply a 10-day average of more than 2 mμc/l of milk at Currant. This is 20 times the limit of Range II recommended by the Federal Radiation Council.[24] Hence, we conclude that radioiodine levels on vegetation even 100 miles from ground zero would have temporarily resulted in levels of I-131 in milk exceeding Range II of the Federal Radiation Council had commercial dairies been operating in these areas.

Appendix A

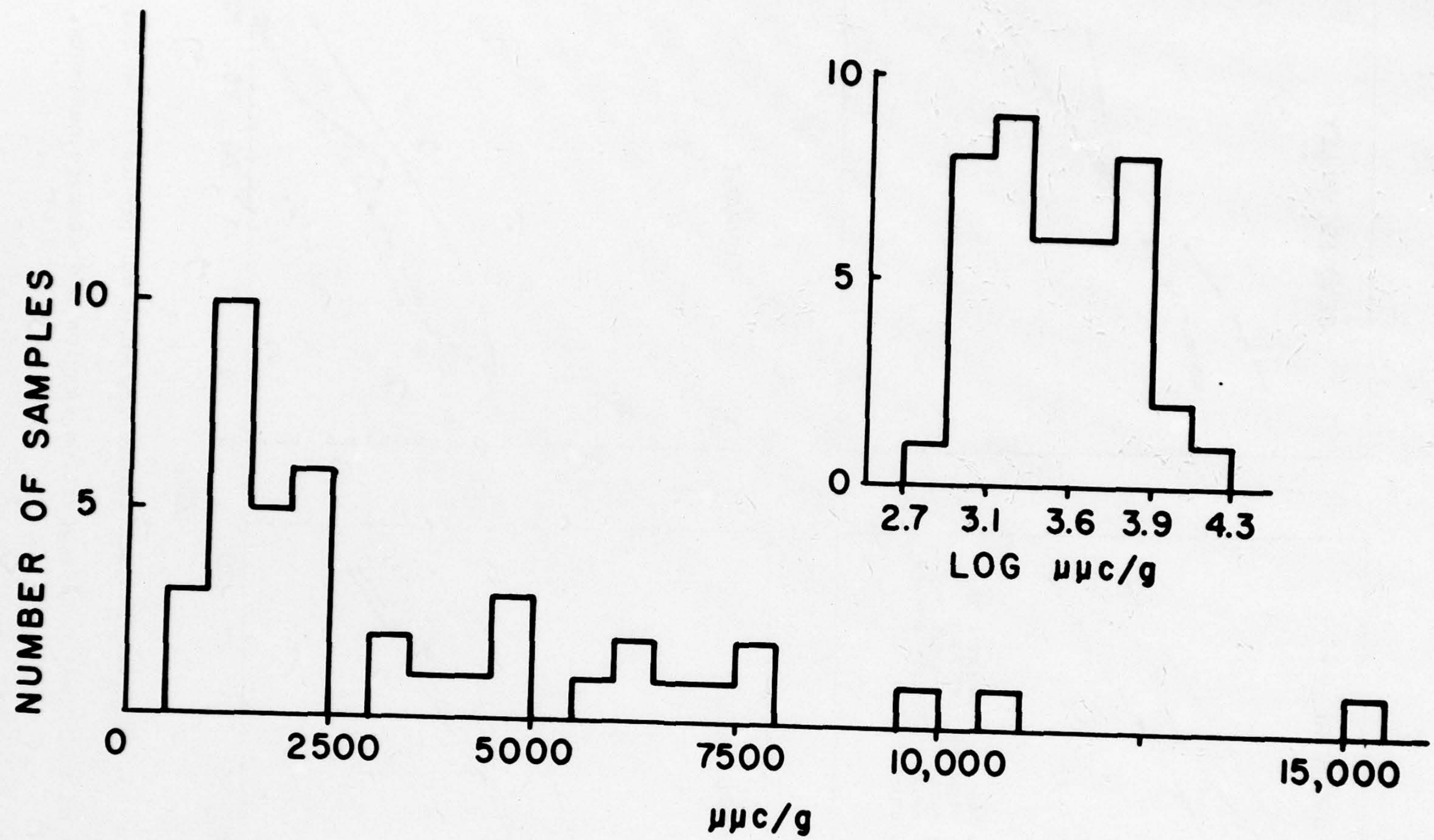
FREQUENCY DISTRIBUTION ASSIGNED TO F IN THE OPERATION OF THE PROBABILISTIC MODEL

Number of cases	Value assigned to F
2	.05
3	.06
3	.07
3	.08
4	.09
5	.10
5	.11
7	.12
7	.13
8	.14
9	.15
10	.16
8	.17
7	.18
6	.19
5	.20
4	.21
3	.22
3	.23
2	.24
2	.25
2	.26
1	.27
1	.28
1	.29
1	.31
1	.32
1	.35

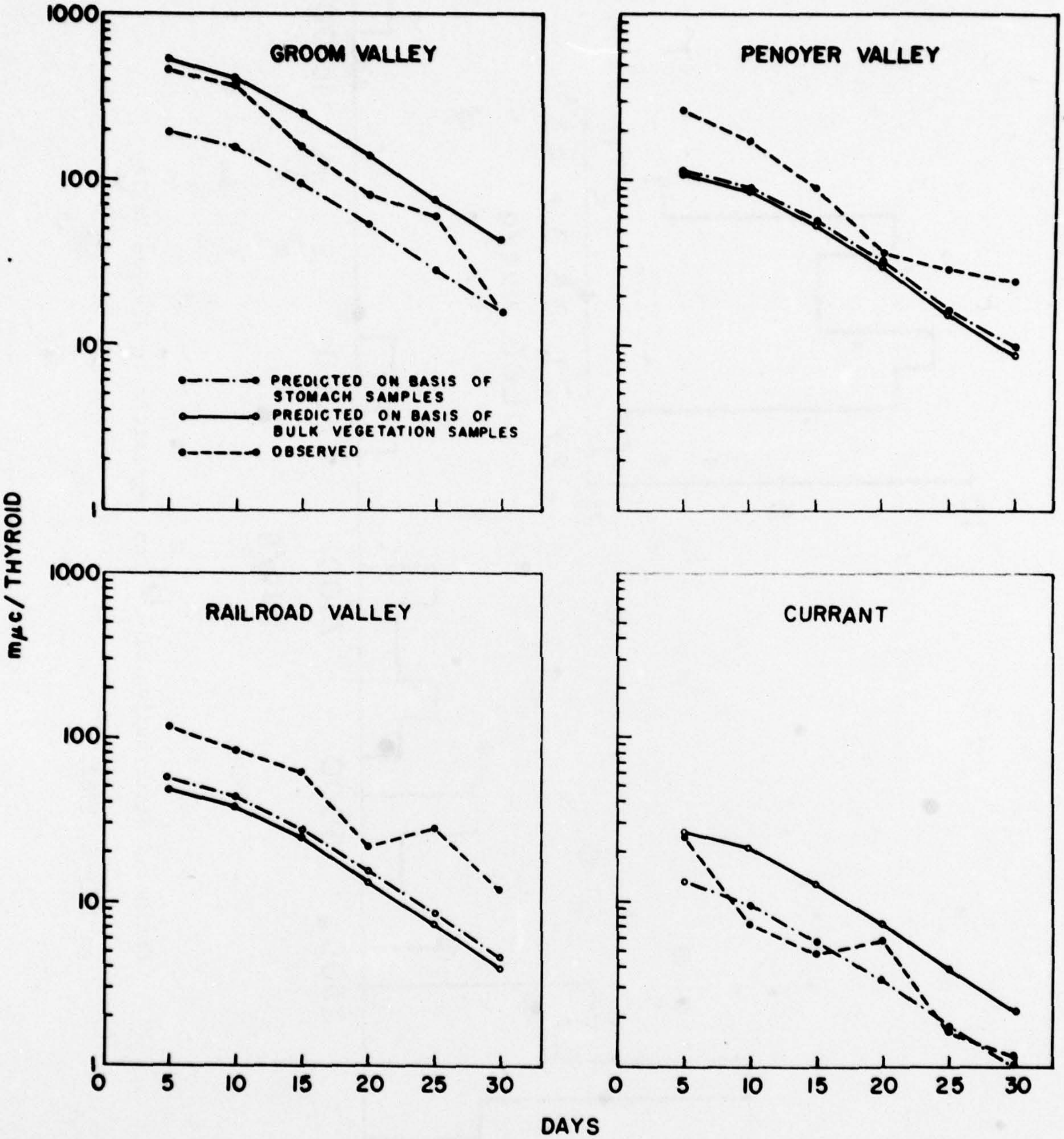
APPENDIX B

PREDICTIONS OF THYROID RADIOIODINE (mμc) BASED ON ANALYSES OF STOMACH CONTENTS (P_s) AND VEGETATION SAMPLES (P_v) COMPARED TO THYROID RADIOIODINE OBSERVED (0)

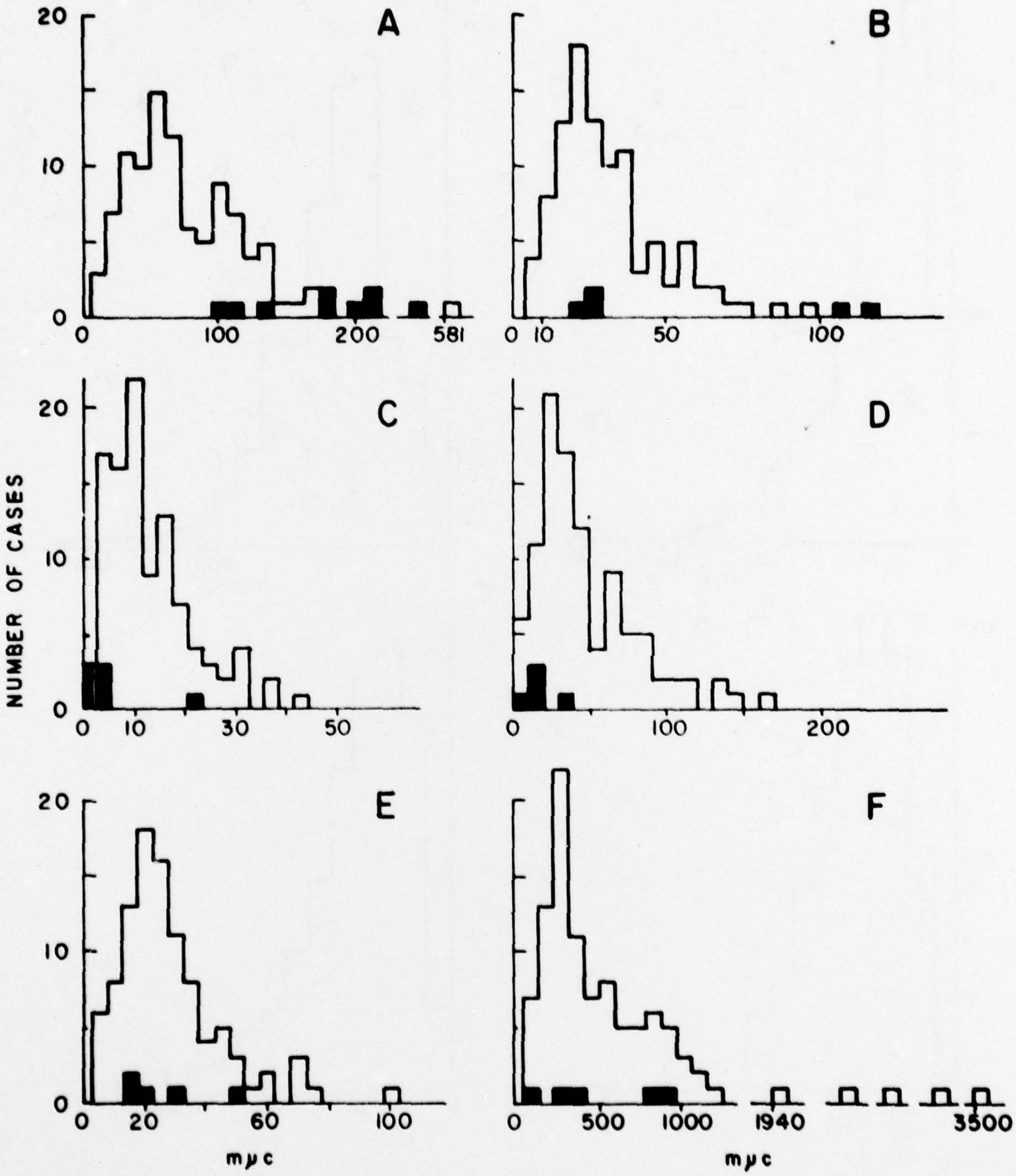
D+	Groom Valley			Penoyer Valley			Railroad Valley			Currant		
	(0)	(P_s)	(P_v)	(0)	(P_s)	(P_v)	(0)	(P_s)	(P_v)	(0)	(P_s)	(P_v)
5	467	195	523	239	117	110	111	59	49	26	12	27
10	386	153	409	188	92	86	85	46	39	7.1	9.7	21
15	160	94	250	90	56	53	61	28	24	4.7	5.9	13
20	83	53	143	37	32	30	22	16	13	5.8	3.4	7.2
25	61	29	78	29	17	16	29	8.8	7.3	1.6	1.8	3.9
30	16	16	43	24	9.4	8.8	12	4.7	4.0	1.1	1.0	2.1



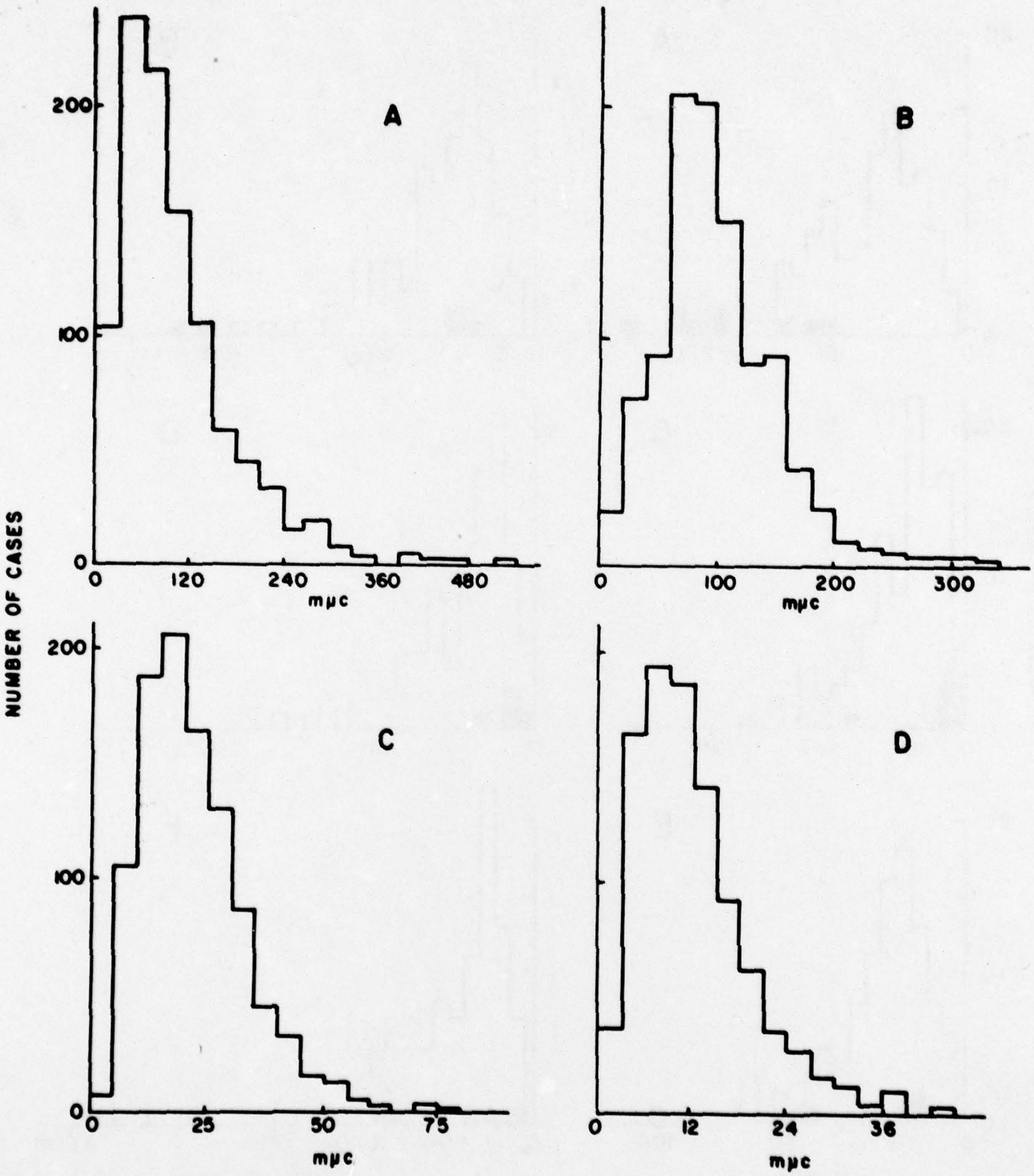
1. Estimated distribution of I^{131} on vegetation in Penoyer Valley on July 6, 1962.



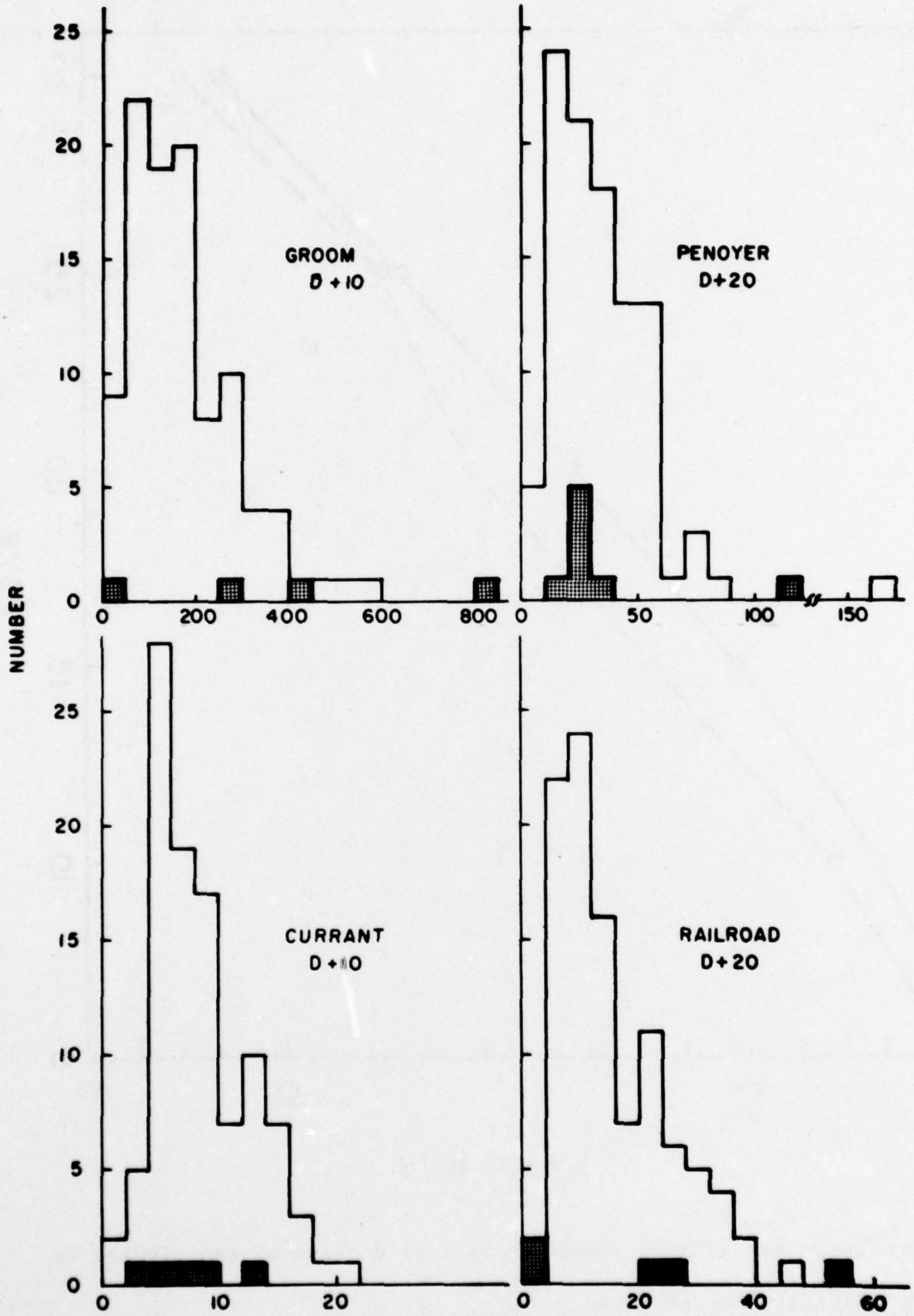
2. Iodine-131 observed in jack rabbit thyroids and predicted on the basis of radioiodine in vegetation samples and stomach contents.



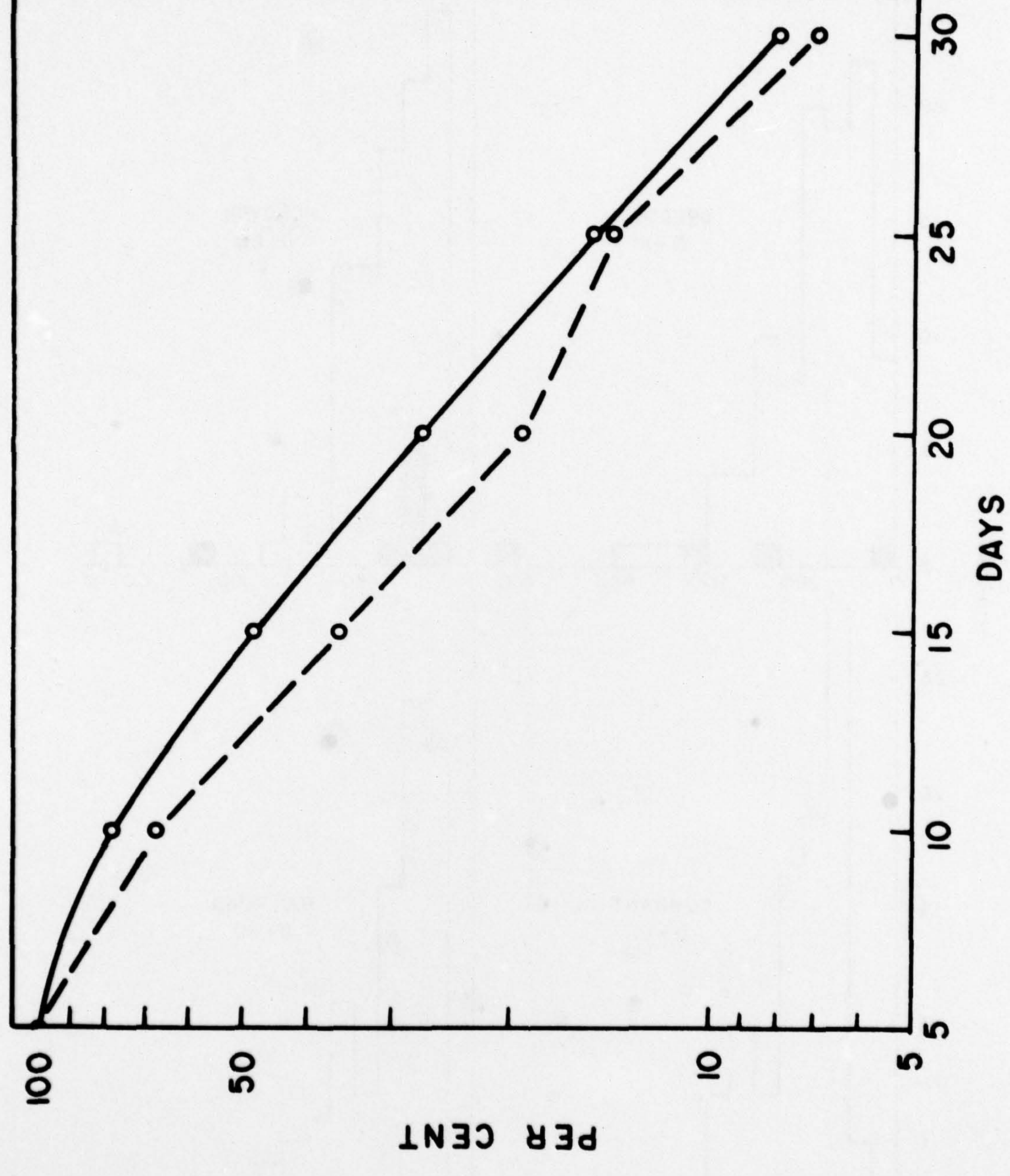
3. Observed amounts of thyroid radioiodine in jack rabbits compared with frequency distributions predicted from radioiodine in vegetation samples.



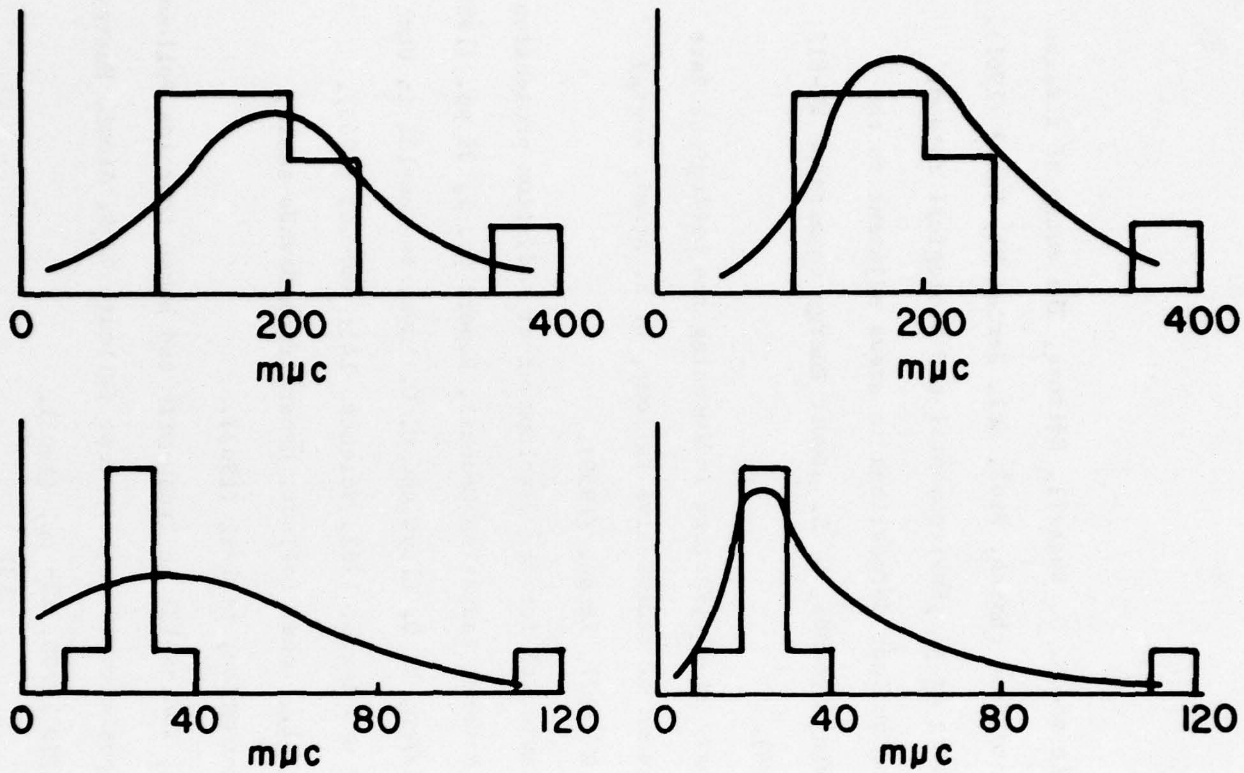
4. Synthetic distributions of 1000 individuals predicted from radioiodine in vegetation samples.



5. Observed amounts of thyroid radioiodine in jack rabbits compared with frequency distributions predicted from radioiodine in stomach contents.



6. **Predicted and average observed rate of decline of radioiodine in thyroids of jack rabbits.**



7. Normal (left) and lognormal (right) distributions fitted to observations of I^{131} in thyroids of jack rabbits from Penoyer Valley during July, 1962.

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SC	Sandia Corporation, Sandia Base, Albuquerque, New Mexico
USC&GS	U. S. Coast and Geodetic Survey, San Francisco, California
LRL	Lawrence Radiation Laboratory, Livermore, California
LRL-N	Lawrence Radiation Laboratory, Mercury, Nevada
Boeing	The Boeing Company, Aero-Space Division, Seattle 24, Washington
USGS	Geological Survey, Denver, Colorado, Menlo Park, Calif., and Vicksburg, Mississippi
WES	USA Corps of Engineers, Waterways Experiment Station, Jackson, Mississippi
EGG	Edgerton, Germeshausen, and Grier, Inc., Las Vegas, Nevada, Santa Barbara, Calif., and Boston, Massachusetts
BYU	Brigham Young University, Provo, Utah
UCLA	UCLA School of Medicine, Dept. of Biophysics and Nuclear Medicine, Los Angeles, Calif.
RDL	Naval Radiological Defense Laboratory, Hunters Point, Calif.
SPHS	U. S. Public Health Service, Las Vegas, Nevada
SWB	U. S. Weather Bureau, Las Vegas, Nevada
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